CONCRETE STRUCTURES UNDER IMPACT LOADING: GENERAL ASPECTS

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Abstract. Dynamic loading conditions distress the structural integrity of a structure differently than the static ones. Such actions transfer high rate strains and instant energy waves to the structure, inducing the possibility of imminent collapse and casualties as a direct consequence. In the latest years, considering the dramatic increase of terrorist threats and global warming, the structural safety criteria imply more than ever the need to withstand this kind of loading (e.g., missiles and blast, projectiles, strong winds, tornados and earthquakes) in addition to the static ones. The aim of this paper is to provide a general overview with regard to impact loading in terms of defining the phenomenon from physical and mechanical perspective, its complex local or global effect on the targeted structure, relevant material characteristics, main research approaches, namely theoretical studies and experimental procedures developed for improving the predictability of the dynamic loads and their effects. New directions in developing superior cementitious composites, with better characteristics in terms of dynamic loading performance are also emphasized.

Key words: dynamic load, concrete, fiber, strain rate, energy absorption

1. Introduction

It is generally known that besides static or quasi-static loads, extreme events (e.g., strong winds, earthquakes, impact hits, blasts and projectile missiles) causing accidental dynamic loading, can brutally affect structural integrity of civil infrastructure, leading to possible sudden collapse and unavoidable casualties. In comparison to the static actions, the predictability of dynamic loads and their effects on the structural elements remain as a real challenge.

Impact represents a severe dynamic load that initially was a major concern within the military research activities. The development of nuclear plants and the risk they unavoidablye brought increased the interest for a deeper evaluation in order to determine the effects of this kind of accidental events on reinforced concrete structures and to develop methods and superior materials to counteract them. The latest years increased level of war and terrorism threats induced an imperative need for impact resistant structures and building materials with improved performance. As consequence, a large number of studies were performed: theoretical and/or analytical models were developed and confirmed or improved by adjacent experimental programs. Additionally, various testing methods, addressing the material or structural performance were calibrated, in a clear attempt to develop impact resistant infrastructure design (Saatci, 2007).

Dynamic loading implies superposition of several physical and mechanical effects which lead to high strain rates and increased energetic peaks that structures have to overcome in a very short time interval. Structural response, local or global, involves a complex interaction of physical and mechanical material properties together with the geometric characteristics of the elements. It synthesizes the structure's capacity/ ability to absorb and release the energy immediately after the hit reached the target, in terms of plastic or elastic deformations as absorbed energy and rebound effect which releases energy to the surrounding environment.

2. Impact - general aspects

Impact can be generally defined as a mass (i.e., the impacting mass) striking another mass (i.e., the impacted mass), under certain conditions of velocity, geometry and material properties of the impacting bodies. It represents a single cycle dynamic loading, unlike the earthquakes which are a multicyclic actions (Marchis *et al.*, 2013).

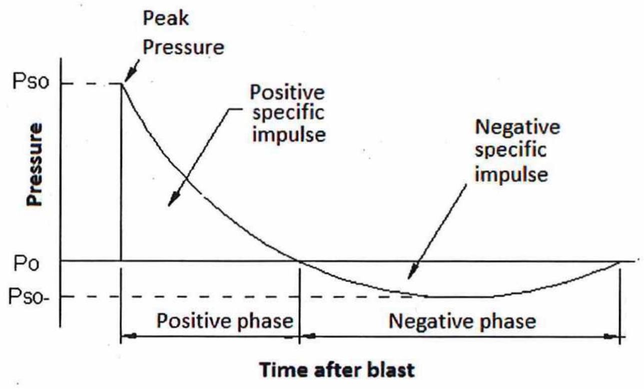

Fig. 1. Typical Blast Load: Pressure history (After Musselman, 2007)

According to Banthia there are two basic categories of impact loadings: single point impact loading (the effect of a missile-like object striking a structural element) and distributed impact loads, e.g., generated by blasts (Banthia, 1987). Further on, the single point impact will be mainly analyzed.

Regarding the second case, structures can be affected by several explosion factors: air blast (the wave of pressure hitting the target as first effect followed by the second one, in terms of the drag load, Fig. 1), primary and secondary fragments, shock of the foundation soil, fire and cratering (Musselman, 2007).

2.1. Impact Physics

There are two basic assumptions concerning the physics of the impact: 1) Conservation of momentum: defined as the product between the mass and velocity of a body, the total momentum of the two objects colliding is kept constant before and after collision:

$$m_1\Delta v_1 + m_2\Delta v_2 = 0 \quad (1)$$

where m_1, m_2 represent the masses of the colliding objects and Δv_1, Δv_2 are their velocities variation during the impact. 2) Conservation of the energy (Fig. 2): kinetic energy (E_k) remains equal to the potential energy (E_p).

Considering the simplified case of a moving object, called impacting body, hitting a standing body called the target with zero velocity in the relative reference system where the couple is placed, it can be stated that the kinetic energy of the striking body will be partially waisted due to the frictional processes (e.g., air or additional contact friction) and partially transferred to the impacted target in the form of stress waves, meaning strain energy and also plastic deformations. The engineering challenge in real structures would then be a proper estimation of their deformability capacity that would ensure their strength in case of accidental loading: the overall structure response has to range in the elastic interval, while still local inelastic deformation can be acceptable.

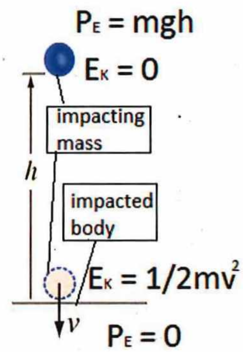

Fig. 2. Typical Impact Load – drop-weight: Conservation of Energy

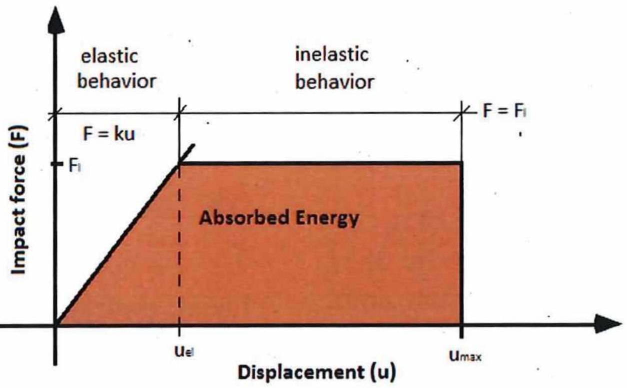

Fig. 3. The ideal elasto-plastic diagram of a body under impact

The ideal elastic model assumes a perfect elastic response of the target, ignoring all friction, damping and plastic deformation, considering only the resulting strain energy of the impact. On the contrary, in reality it will be impossible to avoid inelastic deformations of the impacted body, which can be used as damping solution of the system. From an economical point of view, repair of local damage is preferable to over-dimensioning the structural elements in order to achieve elastic behavior. Fig. 3 presents the perfect elasto-plastic response of an impacted structure.

The initial elastic interval assumes a linear variation of the impact load F=ku, where k and u represent the elastic constant, characterizing the ability of the impacted body to respond to the load, respectively the corresponding deformation. The linear variation stops where yielding starts (no further increase of the loading is possible, $F=F_l$, elastic limit load); the maximum elastic deformation (u_{el}) can be expressed as the F_l/k ratio. The maximum allowed displacement, u_{max}, can be in practice imposed to the value that still ensures the global overall stability of the structure, namely the maximum plastic energy absorption capacity before collapse. The ductility factor μ can be defined as the ratio between the total allowed deformation to the elastic one $\mu=u_{max}/u_{el}$ and it characterizes the energy adsorption capacity of the structure.

The marked area in the diagram (Fig. 3) represents the energy absorbed by the structure when yielding also occurs and the displacement continues without a force increase. The energy conservation principle allows the equality between the energy absorbed by the structure and the work performed by the impact load acting on it:

$$Fu_{max} = \frac{1}{2}F_1u_{el} + F_1(u_{max} - u_{el}) \qquad (2)$$

or

$$\frac{F_1}{F} = \frac{2\mu}{2\mu - 1} \qquad (3)$$

Considering the allowed damage to the structure and assuming an expected impact load, from relations (2) or (3) results the required elastic deformation capacity under an accidental impact.

2.2. Possible Impact

When analyzing a collision situation, the ratio of the colliding masses is considered crucial (Banthia, 1887). Three distinct situations can be identified: 1) The mass of the impacting body (m_1) is substantially larger than the target mass (m_2); 2) The ratio m_1/m_2 is approximately equal to 1; 3) m_1 is substantially smaller than the target mass m_2. The first case is quite rarely met in real structural collisions; the second case involves a global effect on the target (see Fig. 4) and the third one implies only a local effect on the target (Fig. 5).

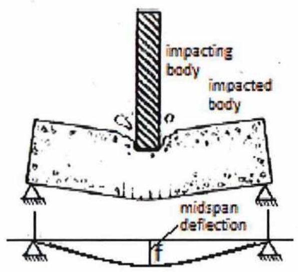

Fig. 4. Global effect of target after missile impact (after Kennedy, 1976)

Local damage can include penetration associated with spalling particles (Fig. 5, a), scabbing as a more sever step (Fig. 5, b), and also complete perforation (Fig. 5, c).

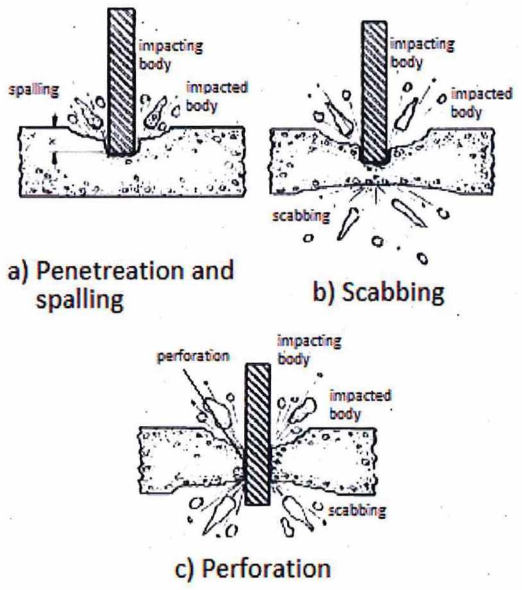

Fig. 5. Local effect of target after missile impact (after Kennedy, 1976)

The impact effect on the target depends also on several other factors, like the toughness ratio of the two colliding bodies and the impact velocity. In the same time, the impacted body might suffer a combination of both, local and global effects (Saatci, 2007).

Taking into account the striking velocity of an impacting body there are two major categories of impact events: high speed impact, ranging from 150 m/s to 1000 m/s (e.g., the case of blast or projectiles) or low speed impact (drop-weight), around just a few m/s.

Hard impact is when the striking object undergoes insignificant deformations in comparison to the target, and soft impact when the striking object develops important damage (Saatci, 2007; Ong *et al.*, 1999).

2.3. Impact mechanics

When a dynamic load is acting, large amounts of stress will be transmitted in short duration to the structural elements, which would have to be able to prove increased deformation capacity for sudden collapse avoidance. Consequently, the structure and the material within would have to possess both strength (for spalling and perforation prevention) and ductility (in terms of energy absorption by the means of strain capacity) (Zhang *et al.*, 2005; Zhang *et al.*, 2007).

The way impact affects the target has a complex nature: despite that initially a compressive wave is generated on the impacted side, as soon as it hits the distal (i.e., boundary free) side of target, it is reflected as tensile stress (Yang and Li, 2012). Fig. 6 shows the stress conversion from compression (blue color) to tensile stress wave (red color) along four distinct, chronological steps.

The stress state generated in the impacted structure undergoes also crushing shear and tensile fracturing (Ramesh *et al.*, 2013), involving interference of material mechanical properties: compressive and tensile strength, toughness, capacity of energy absorbing and dissipation in an extreme short duration, ductility and deformation ability; except from that, ability to withstand spalling and scabbing effects (see Fig. 4 and Fig. 5) and resistance to multiple-impact actions are also essential material and structural characteristics, together with increased *strain rate performance*.

3. Concrete behavior under impact

As previously mentioned, tensile stress is a direct and important effect of the impact loading. The tensile and flexural strength of cement-based composites is significantly lower in comparison with their compressive performance. The concrete fracture toughness, relevant for the intrinsic material capacity to withstand brittle failure, is also quite reduced (around 0.01MPa√m), this affecting concrete structures ability to preserve their integrity under impact. Toughness is introduced as a measure for energy absorbing capacity in the inelastic state, namely resisting fracture when the cracked stage is already induced (Al-Oraimi *et al.*, 1995; Marar *et al.*, 2001).

3.1. Strain rate effect

Dynamic loads imply large amounts of stress transmitted almost instantly (single-cycled loads) to the structural concrete elements of the target, which would have to be able to prove increased deformation capacity for failure prevention. This aspect must be correlated with the strain rate sensitivity of the material, as key for a proper structural design, considering also the loading and boundary conditions of the system. In addition, increasing the complexity of the problem, cementitious composites properties are found to present consistent variations not only at different strain/stress loading rates, but also when different loading and supporting systems are used (Banthia, 1987).

Concrete properties, determined under static or quasi-static loading conditions, are not relevant for an accurate prediction of its performances under high stress rates type of loading, typically for dynamic loads, including impact (Banthia *et al.*, 1989). Several factors, like concrete heterogeneity, inelastic behavior and cement to aggregate variable bonding interface, make it really difficult to establish a general law to map the statically determined characteristics to the dynamic ones.

Cracking, cracking propagation under loading, speed of crack widening, their branching-type propagation pattern in the concrete mass, etc., are examples of mechanical processes that determine the concrete structural failure. In the same context, cracking features of the cementitious composites are crucial for the energy absorbing capacity (e.g., resilience and fracture toughness) and stress/strain rate sensitivity (Suaris and Shah, 1985; Maalej *et al.*, 2005).

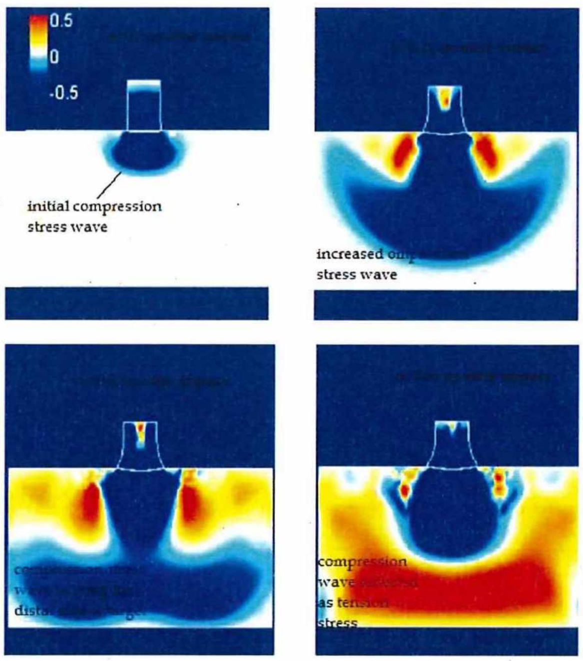

Fig. 6. Stress state under impact: numerical simulation (after Yang and Li, 2012; Shinozuka and Obikawa, 2007)

Dynamic loading and implicitly impact are associated to high strain rates. Some characteristic strain rates related to the loading type are mentioned by Musselman: static and quasi-static loading (e.g., creep) ranges from 10^{-7} to 10^{-6} m/m s^{-1} (strain units per second); multi-cyclic dynamic, seismic type loading ranging from 10^{-3} to 10^{-2} m/m s^{-1}; hard impact, single-cycle load ranges from 10 to 1 m/m s^{-1}; and blast ranges from 10^2 to 10^3 m/m s^{-1} (Musselman, 2007; Bischoff, and Perry, 1991).

The first attempts to identify and understand the causes of the strain/stress/loading rates sensitivity phenomenon started one hundred years ago when Abrams tested concrete cylinders in compression and noticed a significant increase of compressive strength when high loading rate was induced in the specimens (i.e., from impact testing) in comparison with the static test (Abrams, 1917). Other research showed that the general loading rate affects the ultimate compressive strength of concrete only along the second half of the loading interval (Banthia, 1987). Further research in the topic of compression strength under different strain rates were performed by Watstein and also Green, leading to a basically similar conclusion, of an obvious strength increase depending on the loading rate (Watstein, 1953; Green, 1964).

Studies regarding the flexural strength variation of cement-based materials were performed (Zech and Wittmann, 1980), confirming the theoretical relation developed by Mihashi and Izumi, between the static and dynamic strength, as a function of the loading rate and a material parameter β (see Eq. 4), related to the general strength of concrete (Mihashi and Izumi, 1977).

$$f_d / f_s = \left(\dot{\sigma_d} / \dot{\sigma_s} \right)^{\left(1/(1+\beta) \right)} \qquad (4)$$

where f_d and f_s represent the dynamic and static strengths, σ_d^* and σ_s^* are the dynamic and static stress rates and β is a material parameter, which was found to increase as the material strengths increase (Zech and Wittmann, 1980).

Malvar and Ross reported a significant increase of the apparent strength at high strain rates ranging from 1 to 10 m/m s^{-1}: 50% for reinforcing steel, 100% for concrete in compression and over 600% for concrete in tension (Malvaar and Ross, 1998).

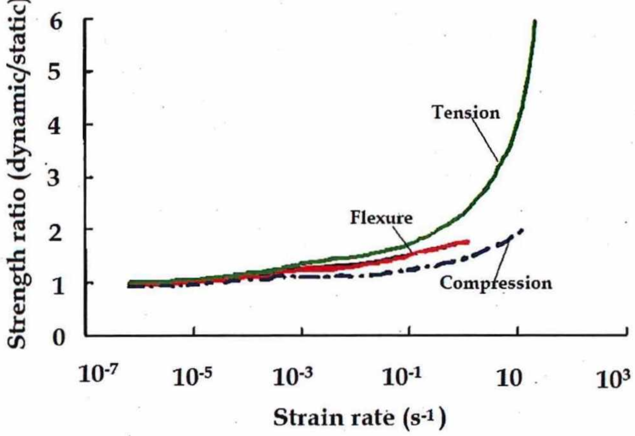

Fig. 7. Plain concrete strain rate effect sensitivity (after Suaris and Shah, 1982; Maalej *et al.*, 2005)

The ultimate strength gain of concrete as a function of the loading rate is considered to derive from two distinct inertial resistance related reasons. The first one is due to lack of time for the crack to find the weakest zone to propagate; instead it might progress through more resistant areas. In the same time, failure will require supplementary cracking events due to the discontinuity of the process (Bischoff and Perry, 1991).

Generally, it has been observed that tension and flexural stress in cement-based composites present higher strain rate sensitivity than the compressive stress, as shown in Fig. 7 (Suaris and Shah, 1982; Maalej *et al.*, 2005). The variation function of the ultimate strain related to the loading rate was found to be rather inconsistent (Fu *et al.*, 1991) in comparison with compressive strength and elastic modulus.

4. Fiber reinforced concrete behavior under impact

The addition of disperse fibers in the cementitious matrices proved to have multiple benefits regarding the overall performance of concrete (Cazan *et al.*, 2014; Văgîi *et al.*, 2012). Starting with the second half of the last century, intensive research has been performed regarding the behavior of the new materials developed using several types of fibers: steel, glass, synthetic (e.g., Kevlar, polymeric fibers like PE, PP and PVA), even natural fibers, like flax or cotton. Apart from increase of the mechanical strength, mainly in tension and bending (Romualdi and Mandel, 1964), the failure pattern was improved by the reduction of brittleness under loading: the crack pattern involves multiple cracking (Fig. 8) and the crack control was modified in such manner that the so called "ductility" of concrete could be achieved, improving the energy absorption and toughness indices as well (Bhargava and Rehnström, 1977).

A problem is still in debate with regard to the compressive strength of concrete, as the fiber addition reduces the tightness of the matrix and some reduction of the compressive strengths have been noticed.

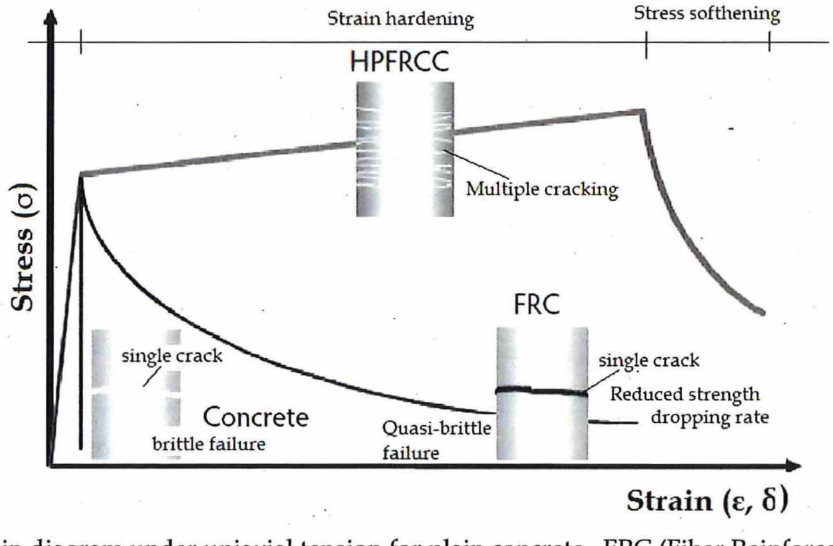

Fig. 8. Stress-strain diagram under uniaxial tension for plain concrete, FRC (Fiber Reinforced Concrete and HPFRCC (after Li, 2008)

It has to be emphasized that fiber addition in the concrete induces an obvious improvement regarding spalling and scabbing, fragmentation, perforation and penetration, as usual phenomena when impact occurs. Fibers keep the matrix particles connected, preventing that spalling pieces would be transformed into dangerous flying projectiles, causing casualties.

There are several factors, fiber-type related, influencing the properties of the cement-based composites: the fiber material (e.g., steel, polymeric, glass, hybrid) and their basic characteristics, geometrical properties and orientation. The mixing and casting techniques are of critical importance too.

4.1. ACI Committee 544; Impact loading

Starting with the 70 ties, the ACI 544 Committee was formed in order to study and evaluate the use of fibers as disperse reinforcement in the cement-based composites. The original State-of-the-Art Report regarding design with Fiber Reinforced Concrete (FRC), first published in 1973 and revised in December 1983, was followed by "Measurement of Properties of Fiber Reinforced Concrete" ACI 544, 2R-89 (ACI Committee 544, 1989), first published in 1978, revised in 1893 and 1988 and reapproved in 2009. This latter report specifies several aspects related to the impact resistance of FRC, including some recommended testing methods to assess their performance. It is also stated that evaluating the impact resistance could involve: 1) Determination of energy necessary to induce fracture; 2) The number of blows in case of a multi-impact test; 3) The size and visual evaluation of the damage produced by impact.

The report includes seven potential testing methods: 1) Weighted pendulum (Charpy) impact test, a method that initially was introduced for metal evaluation and then adjusted to the cement based energy absorption capacity; 2) Drop-weight test, for low velocity impact; 3) The constant strain-rate test; 4) The projectile impact test for high velocity impact; 5) The split-Hopkinson bar test for high strain rate in uniaxial tension and compression; 6) The explosive test; 7) Instrumented pendulum test (ACI Committee 544, 1989).

4.2. Engineered Cementitious Composites (ECC) under Impact

A special type of HPFRCC (High Performance Fiber Reinforced Cementitious Composites) is represented by ECC (Engineered Cementitious Composites), developed initially by Li. With the addition of a volumetric 2% content of fibers, a metal-like behavior, characterized by the strain hardening interval under loading, can be achieved, leading to a high strain effect and superior potential of energy absorption (Li, 1998, 2008). Superior toughness is reached too, as an intrinsic ability to develop bearing capacity after the cracked stage was reached (Maalej *et al.*, 1995; Li and Maalej, 1996). Furthermore, an improved impact resistance of the material is to be expected (Maalej *et al.*, 2005; Zhang *et al.*, 2007).

Regarding the loading rate sensitivity of HPFRCs and particularly ECCs, some studies confirmed that their strength increase can be more substantial than in the case of plain concrete, when high strain rates are applied. The strain capacity under loading seems to remain constant, independent of the stress rate (Maalej and Zhang, 2005; Habel and Gauvreau, 2005). As expected, the hybrid steel and PE fibers mix, showed improved resistance to fragmentation, deformability capacity and high energy dissipation. All these characteristics were attributed to the typical microcracking behavior. In the same time Yang and Li (2012) obtained contradictory results: uniaxial tests were conducted using different strain rates, ranging from 10^{-5} m/m s^{-1} (corresponding to quasi-static loading) to 10^{-1} m/m s^{-1} (relevant for low-speed impact), on the most used PVA-ECC, namely ECC M45. They reached the conclusion of approximately 40 %, drop of the tensile strength in the case of high rate loading and also a dramatic loss of the apparent ductility; from 3.2 % (quasi-static) to a disappointing 0.8 % (high strain rate), in uniaxial tension. As a potential solution to counteract this inconvenience, a substantial increase of the fly-ash content of the matrix is proposed.

The lack of coarse aggregate in the ECC matrix makes this micro-material vulnerable to ballistic penetration, which induces a strong local effect: due to the high velocity of the impacting body and its reduced mass in comparison to the target's mass, there is a predominant local effect. In terms of blast, the energy absorption capacity of the material provides a general overall resistance, superior to the conventional concrete (Maalej and Zhang, 2005).

5. Conclusions

Dynamic loads are complex actions with complex effects on the structures: huge energetic waves converted instantly into high rate stresses that have to be endured by the structural members. The structural performance is depending on the geometry, boundary conditions and material characteristics. Optimum results imply the finding of a balance between the strength (e.g., for penetration and spalling prevention) and deformation capacity (e.g., for energy absorption necessities) in terms of local or global effects.

The current strive for improved structural performance under all types of impact actions (soft and hard, high speed or low speed, etc.) determine the demand for better knowledge on this topic: generous databases regarding the testing methods and material and structural performance under impact, continuous development of design technics and new building materials, that can ensure safety when accidental loading occurs.

The addition of fibers in the concrete matrix proved to provide real benefits for the accidental loading. At the same time, further research is considered necessary, for extending the data base and establishing general and precise testing methodology, which could provide important data and essential characteristics for both, material and structure design criteria.

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REFERENCES

Abrams D. A. (1917), *Effect of rate of application of load on the compressive strength of concrete*, ASTM J **17(2)**:70-78.

ACI Committee 544. (1989), *Measurement of properties of fiber reinforced concrete*, ACI Materials Journal 583-593.

Al-Oraimi S. K., Seibi A. C. (1995), *Mechanical characterisation and impact behaviour of concrete reinforced with natural fibres*, Composite Structures **32(1)**:165-171.

Banthia N. P. (1987), *Impact resistance of concrete,* Doctoral Thesis, University of British Columbia, Vancouver, Canada.

Banthia N., Mindess S., Bentur A., Pigeon M. (1989), *Impact testing of concrete using a drop-weight impact machine,* Experimental Mechanics **29(1)**:63-69.

Bhargava J., Rehnström Å. (1977), *Dynamic strength of polymer modified and fiber-reinforced concretes,* Cement and Concrete Research **7(2)**:199-207.

Bischoff P. H., Perry S. H. (1991), *Compressive behaviour of concrete at high strain rates,* Materials and structures **24(6)**:425-450.

Cazan O. E., Gherman M. C., Boldor R. P., Brata T. M. (2014), *Hybrid fiber reinforced HPC at elevated temperatures,* Acta Technica Napocensis: Civil Engineering & Architecture **57(2)**: 197-202.

Fu H. C., Erki M. A., Seckin M. (1991), *Review of effects of loading rate on reinforced concrete,* Journal of structural engineering **117(12)**:3660-3679.

Green H. (1964), *Impact strength of concrete,* Proceedings of the Institution of Civil Engineers **28(3)**:383-396.

Habel K., Gauvreau P. (2008), *Response of ultra-high performance fiber reinforced concrete (UHPFRC) to impact and static loading,* Cement and Concrete Composites **30(104)**:938-946.

Kennedy R. P. (1976), *A review of procedures for the analysis and design of concrete structures to resist missile impact effects,* Nuclear Engineering and Design **37(2)**:183-203.

Li V. C., Maalej M. (1996), *Toughening in cement based composites. Part II: Fiber reinforced cementitious composites,* Cement and Concrete Composites **18(4)**:239-249.

Li V. C. (1998), *Engineered Cementitious Composites - Tailored Composites Through Micromechanical Modeling,* in: Banthia N., Bentur A., Mufti A., *Fiber Reinforced Concrete: Present and the Future,* Canadian Society for Civil Engineering, Montreal, pp. 64-97.

Li V. C. (2008), *Engineered Cementitious Composites (ECC) Material, Structural, and Durability Performance,* in: Nawy E., Concrete Construction Engineering Handbook, Chapter 24, CRC Press.

Maalej M., Hashida T., Li V. C. (1995), *Effect of Fiber Volume Fraction on the Off-Crack-Plane Fracture Energy in Strain-Hardening Engineered Cementitious Composites,* Journal of the American Ceramic Society **78(12)**:3369-3375.

Maalej M., Quek S. T., Zhang J. (2005), *Behavior of hybrid-fiber engineered cementitious composites subjected to dynamic tensile loading and projectile impact,* Journal of Materials in Civil Engineering **17(2)**:143-152.

Malvar L. J., Ross C. A. (1998), *Review of strain rate effects for concrete in tension,* Materials Journal **95(6)**:735-739.

Marar K., Eren Ö., Celik T. (2001), *Relationship between impact energy and compression toughness energy of high-strength fiber-reinforced concrete,* Materials letters **47(4)**:297-304.

Marchis A. G., Moldovan T. S., Ioani A. M. (2013), *The influence of the seismic design on the progressive collapse resistance of mid-rise RC framed structures,* Acta Technica Napocensis: Civil Engineering & Architecture **55(2)**: 222-234.

Mihashi H., Izumi M. (1977), *A stochastic theory for concrete fracture,* Cement and Concrete Research **7(4)**:411-421.

Musselman E. (2007), *Characterizing blast and impact resistance of long carbon fiber reinforced concrete,* Doctoral Thesis, Pennsylvania State University, USA.

Ong K. C. G., Basheerkhan M., Paramasivam P. (1999), *Resistance of fibre concrete slabs to low velocity projectile impact,* Cement and Concrete Composites, **21(5)**:391-401.

Ramesh K., Arunachalam K., Chakravarthy S. R. (2013), *Experimental Investigation on Impact Resistance of Flyash Concrete and Flyash Fiber Reinforced Concrete,* International Journal of Engineering Research and Applications **3(2)**:990-999.

Romualdi J. P., Mandel J. A. (1964), *Tensile strength of concrete affected by uniformly distributed and closely spaced short lengths of wire reinforcement,* Journal Proceedings **61(6)**:657-671.

Saatci S. (2007), *Behaviour and modelling of reinforced concrete structures subjected to impact loads,* Doctoral Thesis, University of Toronto, Toronto, Canada

Shinozuka J., Obikawa T. (2007), *High levels of hydrostatic stress at shear zone induced by plastic shock waves under ultra high-speed cutting conditions,* in: Proceedings of the 10th CIRP International Workshop on Modeling of Machining Operations, pp. 357-364.

Suaris W., Shah S. P. (1982), *Strain-rate effects in fibre-reinforced concrete subjected to impact and impulsive loading,* Composites **13(2)**:153-159.

Suaris W., Shah S. P. (1985), *Constitutive model for dynamic loading of concrete,* Journal of Structural Engineering, **111(3)**:563-576.

Văgîi V., Măgureanu C., Țibea C. (2012), *Ultra-high performance fiber reinforced concrete: "I" beams and prisms subjected to bending,* Acta Technica Napocensis: Civil Engineering & Architecture **55(2)**: 114-120.

Watstein D. (1953), *Effect of straining rate on the compressive strength and elastic properties of concrete,* Journal Proceedings **49(4)**:729-744.

Yang E. H., Li V. C. (2012), *Tailoring engineered cementitious composites for impact resistance,* Cement and Concrete Research **42(8)**:1066-1071.

Zech B., Wittmann F. H. (1980), *Variability and mean value of strength of concrete as function of load,* ACI Journal **77(5)**:358-362.

Zhang J., Maalej M., Quek S. T. (2007), *Performance of hybrid-fiber ECC blast/shelter panels subjected to drop weight impact,* Journal of Materials in Civil Engineering **19(10)**:855-863.

Zhang J., Maalej M., Quek S. T., Teo Y. Y (2005), *Drop weight impact on hybrid-fiber ECC blast/shelter panels,* Proceedings of third international conference on construction materials: performance, innovation and structural applications, Vancouver, Canada.

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